ROLL-EXPANDED JOINTS IN THE REACTOR ASSEMBLY OF CANDU* PHWRS**

S. Venkatapathi,(1) N.C. Johnston,(2) and A. Mehmi(2)

ABSTRACT

Roll-expanded joints are used extensively in the reactor assembly of CANDU PHWRs and they have performed reliably in commercial power reactors for 25 years. They provide a cost-effective means of joining components of dissimilar materials and enhance the ease of replaceability of the respective sub-assemblies. The joints require no maintenance and they require minimal space.

Each application requires a distinct joint design due to the differences in the service conditions, dimensions and materials of construction of the components, performance requirements and installation considerations.

This paper describes the roll-expanded joints used in the following applications in CANDU reactor assembly: (a) the joint between the zirconium alloy pressure tube and the stainless steel end fitting in the fuel channel assembly, (b) the joint between the liner tube and the end fitting body, (c) the joint between the zirconium alloy calandria tube and the stainless steel calandria-side tube sheet in the calandria, (d) the joint between the fuel channel annulus bellows assembly/fixed-end-stop collar and the lattice tube at the fuelling machine tube sheet, and (e) the joints between the zirconium alloy guide tube and the stainless steel outer hub in the flux detector assembly.

The reasons for selection of the specific roll-expanded joint design for the respective application are presented and design and performance requirements are detailed. Variables in the roll-expansion process and their effect on the properties of the joint designs are discussed. The deformation characteristics of the components and their significance are outlined. The paper summarizes the development, testing and qualification of the roll-expanded joints as well as the operating experience in the CANDU commercial power reactors.

(1) AECL Research, Chalk River Laboratories, Chalk River, Ontario, Canada.

(2) AECL CANDU, Mississauga, Ontario, Canada.

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** Pressurized Heavy Water Reactor

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1. CANDU REACTOR

The calandria vessel in a CANDU reactor calandria assembly (Figure 1), which contains D_2O moderator at 70°C, is a horizontal, cylindrical shell enclosed by two end shield assemblies. Each end shield assembly consists of two tubesheets (calandria and fuelling machine tubesheets, respectively), and is spanned horizontally by 380 or 480 lattice tubes. The lattice tubes in each end shield are arranged on a 286 mm (11.25 in) square pitch to form a circular lattice array. The outboard end of the lattice tube is welded to the fuelling machine tubesheet bore and roll expanded to eliminate any crevice geometry that could result in crevice corrosion.

At each lattice site, a Zircaloy 2 calandria tube, about 6 m (235 in) long, is installed between the calandria tubesheets. A stainless steel insert is installed into the end of the calandria tube. The insert and calandria tube are roll-expanded into the calandria tubesheet, using a "sandwich" joint.

A fuel channel assembly (Figure 2) is installed in each calandria tube. Each fuel channel contains UO_2 fuel and primary heat transport D_2O at a pressure of about 10 MPa and at a temperature ranging from about 250°C at the inlet end to about 300°C at the outlet end. Each fuel channel consists of a Zr-2.5% Nb pressure tube connected to AISI 403 stainless steel end fittings at each end by a roll-expanded joint.
The pressure tube forms the in-core portion of the fuel channel.

The end fittings are the out-of-core extensions to the pressure tubes. They provide connections to various interfacing systems (primary heat transport feeder pipe, fuelling machine and annulus gas system bellows assembly). The outboard end of each end fitting is sealed by a channel closure, which is removed and replaced by remotely operated fuelling machines during on-power fuel-changing operations.

Inside each end fitting resides an AISI 410 liner tube. The liner tube acts as a channel for the movement of the fuel bundles between the fuelling machine and the coolant tube. It also supports and locates the shield plug. Adjacent to the inboard end of the liner tube are a number of holes spaced around the circumference. These holes provide the passage for the coolant between the end fitting and the pressure tube through the shield plug.

In CANDU 6 reactors, the liner tube is roll-expanded into the end fitting just outboard of the pressure tube-to-end fitting joint.

The channel annulus consists of (a) the annular gap between the pressure tube and the calandria tube and (b) the annular gap between the end fitting and the lattice tube. It is isolated from the atmosphere of the reactor vault. The channel annulus is sealed at both ends by bellows assemblies in all CANDU reactors, except BRUCE NGS A, Units 1, 2 and 3, where the channel annulus is closed by a bellows assembly at one end and by a fixed-end-stop collar at the other end. The bellows has a ferrule welded to one end and a flanged sleeve welded to the other end. The ferrule of the bellows (or end-stop collar) is connected to the fuelling machine-end of the lattice tube and the flanged sleeve is welded to the bellows attachment ring which is shrunk on to the end fitting. The roll-expanded joint is one of the methods used to join the bellows assembly to the lattice tube. The fixed end-stop collar is connected to the lattice tube using the roll-expansion process.

The channel annulus is connected to the rest of the annulus gas system by means of a 6 mm (0.25 in) diameter stainless steel (304L) tubing. One end of the tubing is roll-expanded into a hole in the bellows ferrule before being welded to the bellows ferrule.

Vertical and horizontal reactivity control devices are used to provide power-sensing, control and shut-off features. They are installed in the guide tubes, which penetrate the calandria, passing between the calandria tubes. The flux detector unit is one of the control devices and it measures the fission rate within the reactor. The guide tube assembly for the flux detectors is a zirconium alloy (Zircaloy 2) tube that is roll-expanded into a stainless steel (304L) tube at one end.

Roll-expanded joints are used extensively in the reactor assembly of CANDU PHWRs and have performed reliably in commercial power reactors for 25 years. They require minimal space and provide a cost effective means of joining components of dissimilar materials, and enhance the ease of replaceability of the respective sub-assemblies. The joints require no maintenance.

2. PRESSURE TUBE-TO-END FITTING JOINTS

2.1 Joint Description

The pressure tube in a CANDU fuel channel is a cold worked Zr-2.5%Nb seamless tube, 103 mm (4.07 in) inside diameter x 4.1 mm (0.165 in) thick x 6.3 m (248 in) long. It is roll-expanded into the end fittings at each end. The end fitting is fabricated using a modified 403 martensitic stainless steel forging. At the region of the connection to the pressure tube, the body of the end fitting has a tubular section, 165 mm (6.5 in) outside diameter x 25 mm (1 in) thick. Three circumferential grooves are machined at the inside surface of the end fitting.

The pressure tube is roll-expanded into the end fitting to achieve a reduction of 13.5% in the wall thickness of the pressure tube. During the roll-expansion, the pressure tube material is forced into the three grooves in the end fitting, to provide a strong and leak-tight joint (Figure 3).

2.2 Operating Conditions

During reactor operation, the roll-expanded joint is at a temperature of approximately 300°C and is subjected to an internal pressure of about 10 MPa. It is subjected to mechanical loads resulting from the internal pressure, axial loads from the interfacing components, bearing friction, bearing reaction and thermal loads. The rolled joint is in an environment of low neutron flux and low fields of particle and electromagnetic radiations. The inside surface of the pressure tube is exposed to primary heat transport D_2O. On the outside, the inboard end of the roll-expanded region is exposed to the annulus gas (CO_2).

2.3 Design Requirements

During the design life of the fuel channel, the roll-expanded joint must provide a strong, leak-tight and reliable connection between the pressure tube and the end fitting assembly. To address this objective, the roll-expanded joint is required to meet the design requirements of (a) pullout strength, (b) leak-tightness and (c) residual stresses in the pressure tube and the end fitting. The geometry of the inside surface of the pressure tube at the roll-expanded region must permit unrestricted passage for the fuel and provide the necessary support to the fuel.

Maximum acceptable tensile residual stress levels in the pressure tube are specified to mitigate the occurrence of Delayed Hydride Cracking (DHC) in the zirconium alloy pressure tube. The residual stress levels in the end fitting at the roll-expanded region are considered to assess the fracture resistance of the end fitting.

2.4 Applicable Codes and Standards

The joint is designed in accordance with Canadian Standards Association Standard, CAN3-N285-2-M89, "Requirements for Class 1C, 2C and 3C Pressure-Retaining Components and Supports in CANDU Nuclear Power Plants". The codes and standards applicable to the pressure tube-to-end fitting roll-expanded joints are discussed in detail in Reference 1.

2.5 Design by Analysis

The operating stresses in the pressure tube and the end fitting at the roll-expanded region are determined using a finite element stress analysis.

The design rules of the ASME Boiler and Pressure Vessel Code, Subsection NB 3200, are used in the stress analysis. The analysis is included in the stress report of the fuel channel assemblies.

2.6 Design Evolution by Testing

Performance of a roll-expanded joint is affected by the mechanical properties and the geometries of the interfacing components and the fabrication procedures. Analytical modelling of the roll-expansion process is further complicated by the anisotropic nature of the pressure tube material, the dynamic aspects of the roll-expansion process and the existence of a three-dimensional elastic-plastic state in the rolled joint assembly. Therefore, the design of the joint relies heavily on full-scale component tests during feasibility, development and qualification phases in the evolution of rolled joint design. More than 800 pressure tube-to-end fitting roll-expanded joints have been tested during the development programs. Therefore, the joint design is backed by extensive experimental data.

2.7 Factors Affecting Joint Performance

The performance of the pressure tube-to-end fitting roll-expanded joint is affected by: (a) the degree of roll-expansion, (b) the average diametral fit, (c) the material properties and the geometries of the pressure tube and the end fitting, (d) the geometry of the grooves, (e) the alignment between the pressure tube and the end fitting before and during roll-expansion, (f) the condition of the mating surfaces, (g) the length of the joint and (h) the roll-expansion procedures. The effects of the above variables on the performance of the joint are discussed in Reference 1.

During the full-scale component testing, the tests are planned (a) to address the effect of the above variables, both individually and in combination, on the performance of the joint, and (b) to ensure that, within the qualification envelope of the variables, acceptable joints are achieved consistently.

2.8 Degree of Roll-Expansion

The degree of roll-expansion is quantified by the reduction in wall thickness of the pressure tube during roll-expansion. The inside diameter of the pressure tube after roll-expansion is measured in every joint and is used to calculate the wall reduction. The wall reduction, which is calculated per above, is the "apparent" wall reduction, because the increase in the inside diameter of the pressure tube during roll-expansion includes, in addition to pressure tube wall reduction, the permanent diametral growth of approximately 0.05 mm (0.002 in) in the end fitting. The actual reduction in the wall thickness of the pressure tube is measured during the development test programs (Reference 1).

2.9 Production Roll-Expansion of the Joints

The fuel channels are installed in the calandria at the reactor site.

During the installation of the fuel channels, the cleanliness of the components, tools and work area is maintained stringently. Only water-soluble lubricants are used on the rollers. The inspection of the expander and rollers and the replacement of rollers are done on a routine basis at specified intervals. A refinery-type expander is used.

Prior to commencing production, all assembly, roll-expansion and inspection procedures, operators and tooling are qualified by producing a specified number of acceptable joints in a full-scale mock-up of the fuel channel.

Relevant dimensions of the pressure tube and the end fitting are inspected at site to ensure their conformance with the specifications. The pressure tube is trimmed to the required length.

During the fabrication of the CANDU pressure tube-to-end fitting joints, the following fabrication variables are stringently controlled: (a) the nominal apparent wall reduction, (b) the average diametral fit between the outside diameter of the pressure tube and the inside diameter of the end fitting, (c) the axial location of the inboard end of the roll-expanded region relative to the inboard end of the parallel bore in the end fitting, and (d) the alignment between the pressure tube and the end fitting before and during rolling.

After the roll-expansion, the following dimensional measurements are made: (a) the inside diameter of the pressure tube in the roll-expanded region, (b) the axial location of the inboard end of the roll-expanded region and (c) the dimensional measurements, to determine the effect of axial extrusions and rotation of the pressure tube on the geometry of the fuel channel. All rolled joints are subjected to a helium leak test.

2.10 Operating Experience

In early commercial power reactors, constructed before 1975, incorrect roll-expansion procedures produced excessive residual tensile stresses in the pressure tube just inboard of the roll-expanded region. At some of the rolled joints in the earlier reactors, the residual stresses were sufficiently high to initiate DHC in the pressure tube. Seventy-three channels were replaced in the earlier reactors due to DHC occurrence. The revised roll-expansion procedures have eliminated the high stresses in the pressure tube in the reactors which were constructed since 1975.

There are more than 20 000 pressure tube-to-end fitting roll-expanded joints in the twenty four CANDU commercial power reactors in operation.

Except for the joints in the seventy-three channels mentioned above, the joints have not caused any reactor incapability.

The ease of replaceability of the fuel channel has been demonstrated by the successful large scale fuel channel replacements in the four reactors in Pickering NGS A, and by the routine single fuel channel replacements in various reactors for pressure tube surveillance examinations.

The rolled joints from the fuel channels, which were removed from the reactor after service, have been tested to determine their pullout strength and residual stresses. The post-service pullout tests have confirmed that the in-reactor service did not affect the strength of the rolled joint.

The residual stresses in the pressure tube decrease during reactor service, due to stress relaxation. The post-service measurements of the residual stresses have validated the theoretical model that was developed to calculate the extent of the stress relaxation during reactor service (Reference 1).

Recent research and development efforts in pressure tube-to-end fitting roll-expanded joints are addressing: (a) the improvements to the geometry of the inside surface of the pressure tube at the roll-expanded region, to improve the fuel passage, (b) design of the joints for the next generation of fuel channels with improved replaceability, (c) mitigation of life-limiting factors (e.g., deuterium ingress), and (d) the development of an analytical finite element model to simulate the roll-expansion process and predict the performance characteristics of the joint.

3. CALANDRIA TUBE-TO-TUBESHEET JOINTS

3.1 Joint Description

The calandria tube in a CANDU reactor is a large-diameter tube, 1.37 mm (0.054 in) thick and about 6 m (235 in) long, made from a Zircaloy 2 strip. The inside diameter of the body of the tube is 129 mm (5.077 in). The end sections, 148 mm (5.8 in) in length, are flared to an inside diameter of 140 mm (5.502 in).

Calandria tubesheets (304L), to which the calandria tubes are joined at both ends, are 40 mm (1.56 in) thick at the joint.

The geometry of the calandria tube (high (inside diameter/wall thickness) ratio) does not favour the use of conventional roll-expanded joints. The joint design must not cause unacceptable distortion to the tubesheet and it must not induce excessive tensile and torsional residual stresses in the calandria tube. The above conditions necessitated the development and qualification of a unique joint: namely, a "sandwich" type roll-expanded joint.

Figures 4 and 5 show the design of a typical calandria tube-to-tubesheet joint. Figure 4 shows the assembly before rolling. The tubesheet has a wide groove and two narrow grooves outboard of it. The calandria tube is located in the tubesheet bore.
An insert is installed within the end of the calandria tube. The insert is made of stainless steel (type 410). The insert has a mating land to match the wide single groove in the tubesheet. During roll-expansion, the insert is expanded until the land on the insert forces the calandria tube material into the mating groove in the tubesheet. After all the clearances between the insert, calandria tube and the tubesheet are taken up, the tubesheet is further roll-expanded, until the required reduction in the wall thickness of the insert is obtained and the material in the insert shoulder is forced into the two narrow grooves in the tubesheet. Figure 5 shows the joint in the roll-expanded condition.

3.2 Operating Conditions

During its operating life, the inboard end of the joint is exposed on the outside to the moderator D_2O (at 70°C), and to the additives that are added to the moderator to control reactivity. The atmosphere inside the calandria tube consists of annulus gas (CO_2) and its radiolysis products. The joint is exposed to the thermal radiant heat from the pressure tube surface, which is at a temperature of approximately 300°C. The rolled joint is also subjected to neutron flux and alpha, beta and gamma radiations.

3.3 Design Requirements

The calandria tubes act as stays between the calandria end shields. Therefore, the joint must transmit, between the tubesheet and the calandria tube, the loads resulting from normal and accident conditions. The loads are axial, bending and thermal loads, and the loads due to in-reactor deformation of the calandria tube.

The joints are required to withstand pullout loads sufficient to cause failure of the calandria tube remote from the joint.

The joint is a part of the pressure boundary for the moderator system, and therefore must form a water-tight seal to prevent leakage of moderator into the annulus gas system.

The joint must perform reliably throughout its design life, so that its contribution to the reactor incapability can be shown to be almost zero. The joint must not require any maintenance, because it is inaccessible after the fuel channel is installed.

3.4 Applicable Codes and Standards

The joints are designed to the requirements of the Canadian Standards Association Standards CAN/CSA-N285.0-M91, CAN/CSA-N285.1-M91 and CAN/CSA-N285.2-M89, which also refer to the applicable rules in the ASME Boiler and Pressure Vessel Code, Section III.

3.5 Design Evolution

Similar to other roll-expanded joint designs, the design of the calandria tube-to-tubesheet rolled joints has evolved through feasibility tests and development and qualification programs test programs, in which more than 200 joints have been tested. The programs were formulated to ensure (a) that the qualification envelope covered the range of all variables, and (b) that, within the qualification envelope, the joint design met the design requirements.

3.6 Factors Affecting Joint Performance

The variables in the fabrication of a calandria tube-to-tube sheet roll-expanded joint are (a) the yield strength ratio (hardness ratio) of the tubesheet-insert combination, (b) degree of roll-expansion and (c) the dimensions of the mating components. Since the material properties of the tubesheet and insert are specified to be within a narrow range, the variation in the strength ratio is limited to the combination of the extremes in the achieved material properties of the individual components resulting from heat-to-heat variations. The effect of the variables on the joint performance are detailed in Reference 2.

3.7 Degree of Roll-Expansion

The degree of roll-expansion is specified as the reduction in the wall thickness of the insert due to roll-expansion. The inside diameter of the insert after rolling is used to calculate the reduction in the insert wall thickness. The joints are fabricated to achieve an increase in the insert diameter ("diametral wall reduction") of approximately 0.51 mm (0.020 in).

3.8 Production Roll-Expansion of the Joint

In contrast to the fuel channel installation, the calandria tubes are installed during the fabrication of the calandria at the manufacturer's shop.

Each calandria tube is trimmed to suit the distance between the calandria tubesheets at the specific lattice site. The dimensions of the tubesheet bore, the insert and the calandria tubes are measured to ensure their conformance with the requirements.

The calandria tube is inserted through the lattice tube bore and is positioned in the bore of the tubesheet. The sleeve insert is installed in the calandria tube bore at the specified axial location. A refinery-type expander is used for the fabrication of the joint. The expander is set to achieve the required reduction in the wall thickness of the insert. During roll-expansion, the insert is held axially until all the radial clearances between the components are eliminated. The axial restraint on the insert is then removed and the roll-expansion is continued, thereby allowing the axial extrusion of the insert during its wall reduction. After the completion of roll-expansion, the inside diameter of the insert and the axial extrusion are measured. Each joint is subjected to a helium leak test.

The dimensions of the tubesheet bore, calandria tube and the insert are held within a narrow tolerance range, thereby allowing the option to roll-expand all the joints in a reactor to a standard inside diameter of the insert (after roll-expansion).

3.9 Operating Experience

No evidence of deterioration in the joint performance has been observed in any of the 20 000 joints in the operating CANDU commercial power reactors.

Individual calandria tubes have been successfully replaced since 1968, thereby confirming their ease of replaceability.

The programs in progress are addressing the development of the joints for the calandria tube designs that are being developed to meet the requirements of the next generation of CANDU reactors.

4. LINER TUBE-TO-END FITTING JOINTS

4.1 Joint Description

The liner tube is made from seamless tube manufactured in accordance with the requirements of ASTM-A268, Grade TP-410.

The inside diameter of the liner tube is 104 mm (4.09 in). The outside diameter of the tube, at the region to be expanded into the end fitting, is 112.7 mm (4.437 in). The end fitting body, at the location of the liner tube joint, has an inside diameter of 112.8 mm (4.442 in) and is about 25 mm (1 in) thick. The liner tube-to-end fitting joint in CANDU 6 reactors is a one-groove roll-expanded joint (Figure 6). The liner tube is roll-expanded to a nominal reduction of 7% in the wall thickness of the liner tube.

4.2 Operating Conditions

During operation, the liner tube joint is exposed to primary heat transport D_2O. The liner tube and the joint are not pressure boundary components.

4.3 Design Requirements

One of the functions of the liner tube is to locate and support the shield plug. The shield plug locates the fuel bundles in the fuel channel and it is held in position in the liner tube by a latch mechanism. To facilitate remote on-power fuelling, the liner tube joint must position the liner tube accurately, relative to the outboard (fuelling machine) face of the end fitting.

The liner tube joint must resist the axial loads imposed by on-power fuelling operations without any axial movement of the liner tube. The joint must be able to withstand, without failure, the pressure load imposed through the shield plug, in the unlikely event of the ejection of the channel closure. The joint must allow a smooth and unimpeded passage of the fuel. The joining process must not deform the flow holes in the liner tube.

4.4 Development of the Joint

The liner tube joints were first used in Douglas Point NGS, which was the first CANDU (prototype) power reactor to use the fuel changing concept similar to that used in CANDU 6 reactors. The joint design was similar to the present design, except that two grooves were used.

The development program, which consisted of testing a number of joints, confirmed that (a) the strength requirements were met, (b) the axial extrusions in the liner tube were small enough to allow accurate positioning of the liner tube, and (c) the roll-expansion did not affect the end fitting or weaken the liner tube at the flow-hole locations.

The development tests were repeated during the design of the fuel channel for Pickering NGS A, the first commercial power reactor to use liner tube joints. The joint was a single-groove design. The joint was qualified by a test program similar to the earlier program described above.

4.5 Factors Affecting Joint Performance

The relative mechanical strengths of the liner tube and the end fitting body and the degree of roll-expansion affect the strength of the joint. The degree of roll-expansion, quantified by the reduction in the wall thickness of the liner tube, must be optimized to attain the required strength while resulting in a minimal, if any, deformation of the liner tube.

4.6 Production Roll-Expansion of the Joint

The liner tube is roll-expanded into the end fitting by the manufacturer of the end fitting. The roll-expansion procedure, tooling and personnel are qualified by the fabrication of three acceptable pre-production joints. Prior to roll-expansion, the liner tube is so located that its final post-roll position would conform to the specified requirements. Each liner tube is custom-roll-expanded to achieve the specified reduction in the wall thickness of the liner tube. The reach of the expander is set to avoid any distortion of the flow holes during roll-expansion.

Each joint is subjected to (a) dimensional inspections, to assure that the required wall reduction is achieved and that the fuel passage is unimpeded, and (b) a visual examination.

4.7 Operating Experience

There are about 9 200 liner tube roll-expanded joints in operation and they have performed satisfactorily. They have not contributed to any reactor incapability.

5. FUEL CHANNEL ANNULUS BELLOWS-TO-LATTICE TUBE JOINT

5.1 Joint Design

The bellows assembly, which seals the annulus between the end fitting and the lattice tube, is provided with a stainless steel (304L) ferrule at one end. The outside diameter of the ferrule is 197.2 mm (7.764 in) and its wall thickness is 4.47 mm (0.176 in). The ferrule is roll-expanded into the lattice tube (304L) at the fuelling machine tubesheet. The lattice tube inside diameter at the joint region is 187.5 mm (7.775 in).

Figure 7 shows the details of the two-groove roll-expanded joint. The joints are roll-expanded to a standard inside diameter to achieve a reduction of around 7.3% in the wall thickness of the bellows ferrule.

5.2 Operating Conditions

The joint is exposed to the annulus gas (CO_2) on the inside surface, and the outboard end is in the dry air between the fuelling machine tubesheet and the feeder insulation panels. The ambient temperature is about 260°C. The joint is in a low neutron flux and gamma radiation field environment.

5.3 Design Requirements

As a part of the bellows assembly, the joint must withstand the axial loads due to thermal changes, and the in-reactor elongation of the pressure tube and the torsional moment from the feeders. The joint must meet the leak-tightness requirements of the gas annulus system.

5.4 Applicable Codes and Standards

The joint is a part of the gas annulus system and is designed in accordance with CSA/CAN3-N285-0-M81, "General Requirements for Pressure Retaining Systems and Components in CANDU Nuclear Power Plants".

5.5 Development Tests

Pickering NGS A, unit 1, was the first CANDU reactor to use a sealed annulus gas system. The design featured a roll-expanded joint to connect the bellows assembly to the lattice tube.

The design was developed and qualified by a test program. The primary variable in the test program was the degree of roll-expansion: namely, reduction in the bellows ferrule wall thickness by roll-expansion. A number of joints were subjected to a dimensional inspection, to quantify the axial extrusions and the rotation of the bellows ferrule and the distortion of the ferrule and the lattice tube (tubesheet) during roll-expansion. Helium leak tests were performed in the as-roll-expanded condition. During the torsional resistance tests, the torsional moment was imposed on the joint, in steps. At each load increment, the torsional moment was unloaded and the joint was examined for any permanent rotation or damage. The axial strength of the joint was determined by pullout tests. A temperature-cycling test, with intermediate helium leak tests at the elevated temperature, was also performed. The development tests demonstrated that the joint design met the requirements.

5.6 Production Roll-Expansion of the Joints

In the reactors where the bellows to lattice tube joints are roll-expanded, annulus bellows are installed at the reactor site during the installation of fuel channels. The joints are roll-expanded to achieve a standard (roll-expanded) inside diameter of the ferrule. This diameter corresponds to a reduction of 7.3% ± 2.1% in the wall thickness of the ferrule, taking into consideration the dimensional tolerances of the interfacing components. The inside diameter at the joint is measured and recorded. On completion of the fuel channel installation, the gas annulus system, including the joints, is subjected to a pressure test.

Prior to production installation, pre-production joints are fabricated to qualify all personnel, tooling and the procedure. The pre-production joints are subjected to a leak test.

5.7 Operating Experience

The rolled joint design is used in sixteen reactors and has performed reliably.

6. FIXED END-STOP COLLAR TO LATTICE TUBE JOINT

In Bruce NGS A, Units 1, 2, and 3, the end fitting at the fixed end of the fuel channel was joined to the end shield using a fixed end-stop collar instead of the bellows assembly.

The end-stop collar was made of carbon steel to the requirements of ASTM A105 or ASTM A106. The collar was joined to the lattice tube using two roll-expanded joints. The joint design is shown in Figure 8. The outboard joint, location "A" in Figure 8, is a two-groove joint. It is roll-expanded to achieve a nominal reduction of 7.3% in the wall thickness of the end-stop collar. The joint provides leak-tightness and axial strength. At the inboard location, "B", an ungrooved joint is roll-expanded to attain a nominal reduction of 2.5% in the wall thickness of the end-stop collar. This results in a residual interference between the components and imparts bending strength to the joint to withstand the loads resulting from supporting the fuel channel.

Operating conditions are identical to those of the annulus bellows-to-lattice tube joints. In addition to the design requirements of the annulus bellows joints, the end-stop collar joint must withstand the vertical loads and bending moments resulting from supporting the fuel channel.

The joint design was qualified by development tests. The joints were subjected to a combination of axial, bending and torsional loads and temperature cycles, and leak tested.

During production installation at reactor site, the end-stop collar was accurately positioned in the lattice tube. The outboard joint at location A was roll-expanded before roll-expanding the inboard joint at location B. The joints are fabricated to obtain standard inside (roll-expanded) diameters of the end-stop collar at their respective locations. A leak test was performed.

The 1 440 joints, which are in service, have been free of any malfunction.

7. JOINTS IN FLUX DETECTOR GUIDE TUBES

7.1 Joint Design

Figure 9 shows one of the designs of the joint between the stainless steel tube and the Zirconium alloy tube in a guide tube assembly for the flux detector. The Zircaloy 2 tube, 20.8 mm (0.82 in) outside diameter x 1.1 mm (0.043 in) wall thickness, is connected to the 304L outer hub 33.5 mm (1.34 in) outside diameter x 21 mm (0.827 in) inside diameter.

Three grooves are machined at the inside surface of the outer hub. Prior to final machining, the bore of the outer hub is work-hardened. The Zircaloy 2 tube is roll-expanded to 13.5% reduction in its wall thickness.

7.2 Operating Conditions

On the outside surface the joint is exposed to D_2O moderator at about 70°C. The inside surface of the joint is exposed to helium. The joint is subjected to the external pressure due to the moderator system.

7.3 Applicable Codes and Standards

In reactors where the guide tubes form part of the reactor containment boundary (during the maintenance of the flux detectors), the joint is designed to the requirements of the ASME Boiler and Pressure Vessel Code, Section III, Class 2.

7.4 Joint Development

During the development tests to qualify the joint design, the joint was thermally cycled 1000 times between 38°C and 121°C and the joint remained helium leak-tight.
The strength of the joint was equivalent to that of the Zircaloy 2 tube.

7.5 Production Roll-Expansion of the Joints

The joint is fabricated by the manufacturer of the flux detector assemblies.

Prior to roll-expansion, the components are positioned so that the final assembly will meet the specified dimensional requirements. A refinery-type expander is used. Similar to pressure tube and liner tube joints, the guide tube joints are custom-roll-expanded. The joints are subjected to a helium leak test with the external helium pressure. A specified axial tensile load is applied to the joint during the helium leak test. The helium leak rates of the joints must meet the specified requirements.

7.6 Operating Experience

The guide tube joints have performed to their requirements in the commercial power reactors. They have not contributed to any reactor incapability.

8. OTHER APPLICATIONS OF ROLL-EXPANSION

Roll-expansion has also been used during the fabrication of the end shield, to generate interference between components to eliminate crevices and thereby avoid crevice corrosion.

During gas annulus tubing installation, the process is used to prevent any rotational movement during welding.

9. CONCLUSION

The conceptual designs of the above joint designs were initiated to address well-defined requirements. Their evolution has been based on years of experience. They were developed and qualified by extensive and well-controlled test programs using full-scale components, and by analyses.

The components are manufactured to stringent specifications. The component manufacture, and their assembly and joining processes are subject to strict quality control. Prior to production of the joints, the personnel, the procedure and the tooling are qualified by mandatory qualification tests using full-scale components. The post-service surveillance examinations of the joints are undertaken to evaluate their fitness for service.

The above measures have made the roll-expanded joints one of the reliable design elements in the design of CANDU commercial power reactors. The mission of the on-going development of the joint concepts for the next generation of CANDU reactors is to conform to this high performance standard.

10. ACKNOWLEDGEMENT

This paper summarizes the work performed at GE Canada, Westinghouse Canada (Canadian Westinghouse Company Limited) and AECL since the 1960s. The programs were sponsored and funded by Ontario Hydro and AECL and the CANDU Owners Group.

The authors are indebted to their co-workers (too numerous to name), whose input was invaluable in the preparation of this paper.

This paper is dedicated to E.H. Farris of GE Canada. His contribution, during his entire professional career (thirty seven years!), to the design, development, testing and production of roll-expanded joints is well-respected and appreciated in the CANDU fraternity. His knowledge, experience, insight and diligence have been an inspiration to those associated with the CANDU reactor design.

11. REFERENCES

1. Venkatapathi, S., Mehmi, A., and Wong. H, "Pressure Tube-to-End Fitting Roll-Expanded Joints in a CANDU PHWR", International Conference on Expanded and Rolled Joint Technology, 1993 September.

2. Venkatapathi, S., and Johnston, N.C., "Calandria Tube-to-Tubesheet Roll-Expanded Joints in CANDU PHWRs", International Conference on Expanded and Rolled Joint Technology, 1993 September.

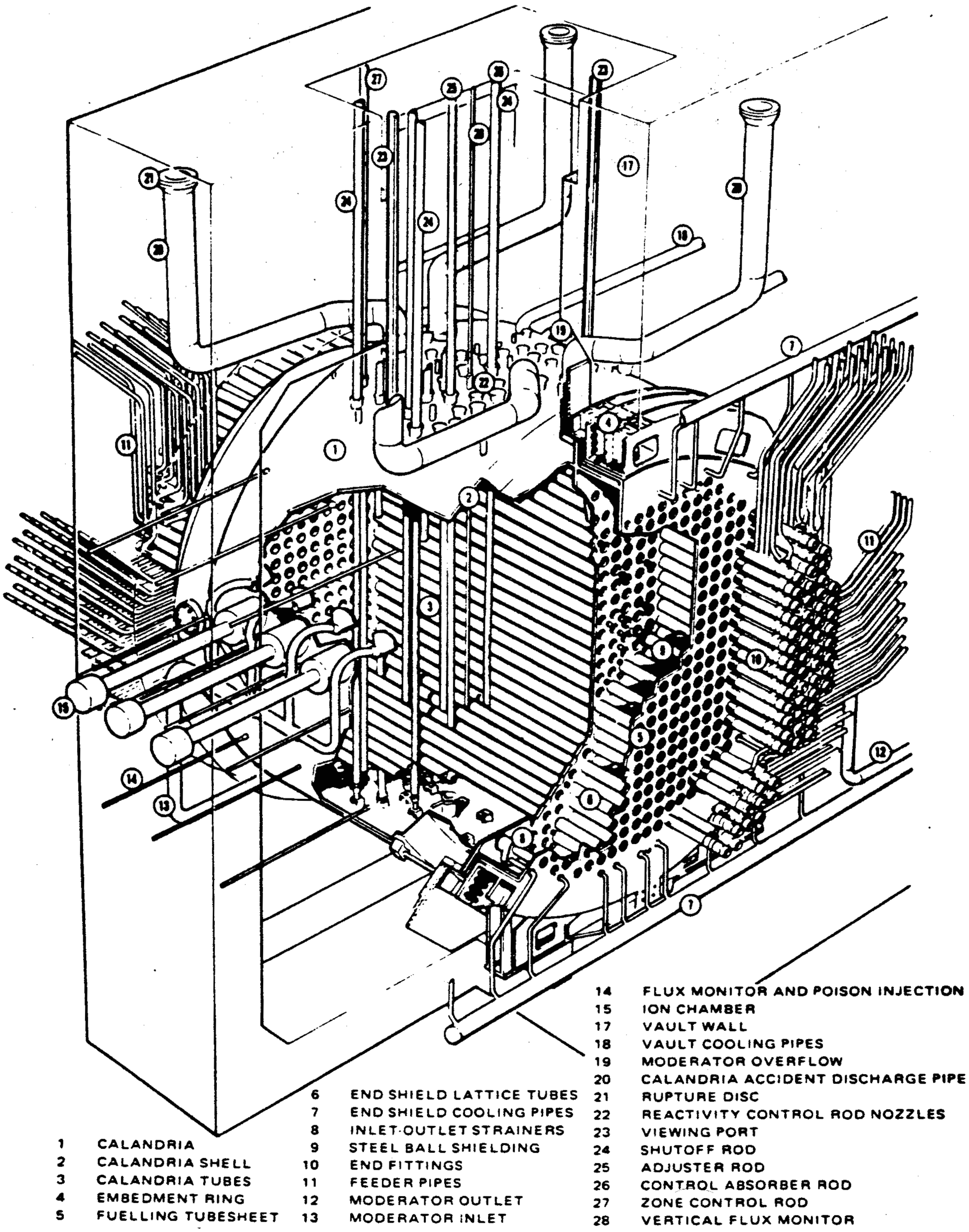

Figure 1: CANDU 6 Reactor Assembly

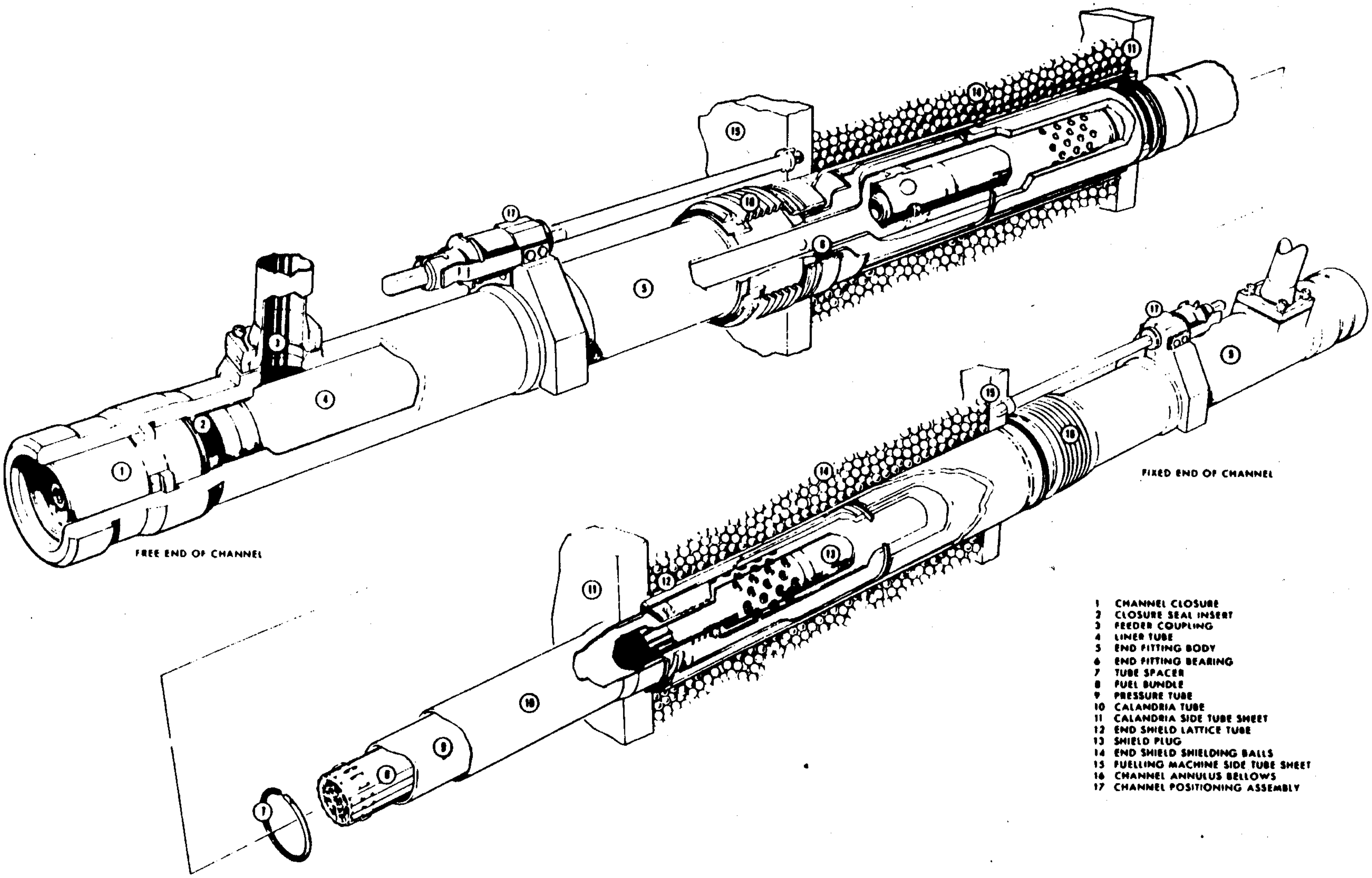

Figure 2: CANDU 6 Fuel Channel Assembly

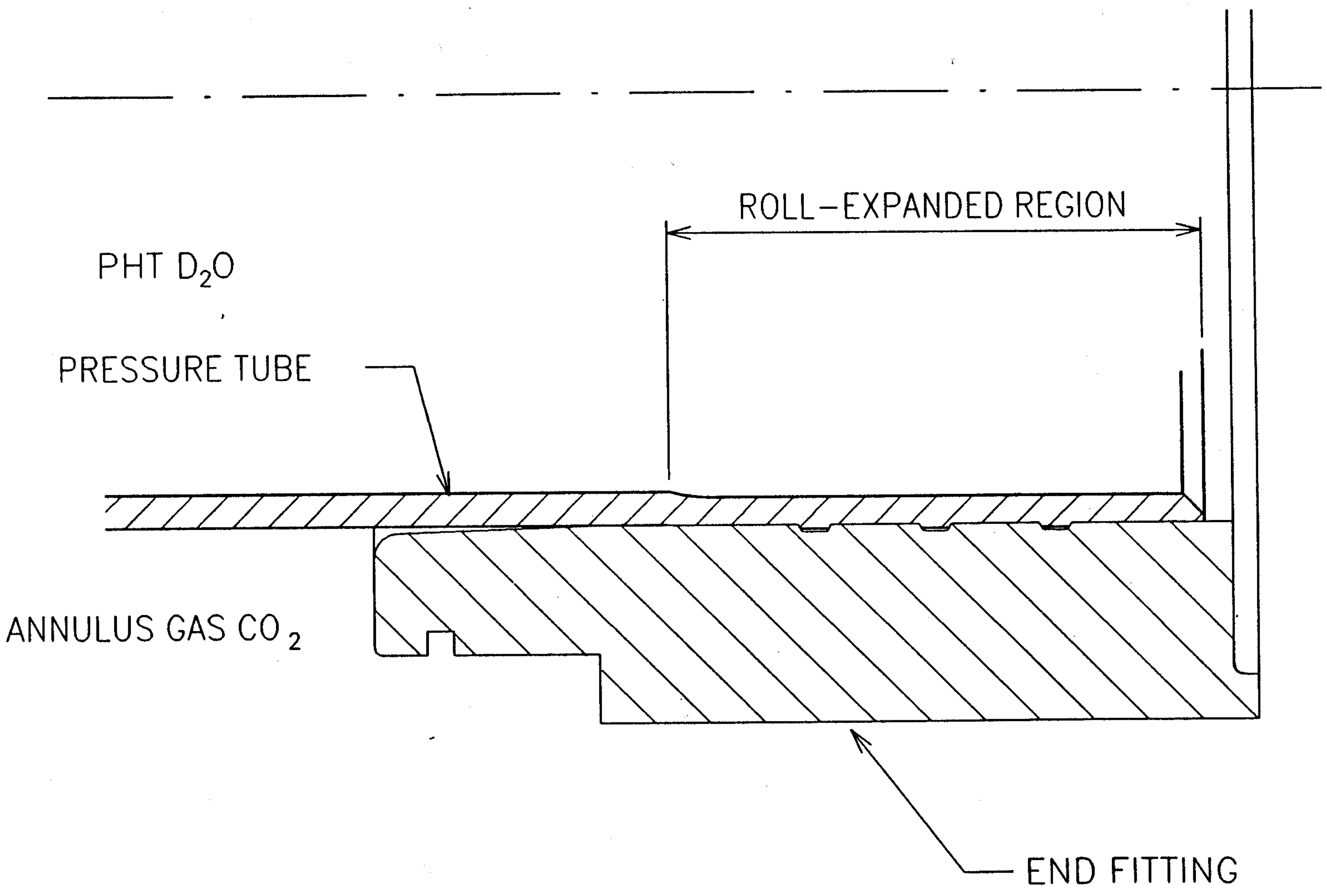

Figure 3: **Pressure Tube-to-End Fitting Roll-Expanded Joint**

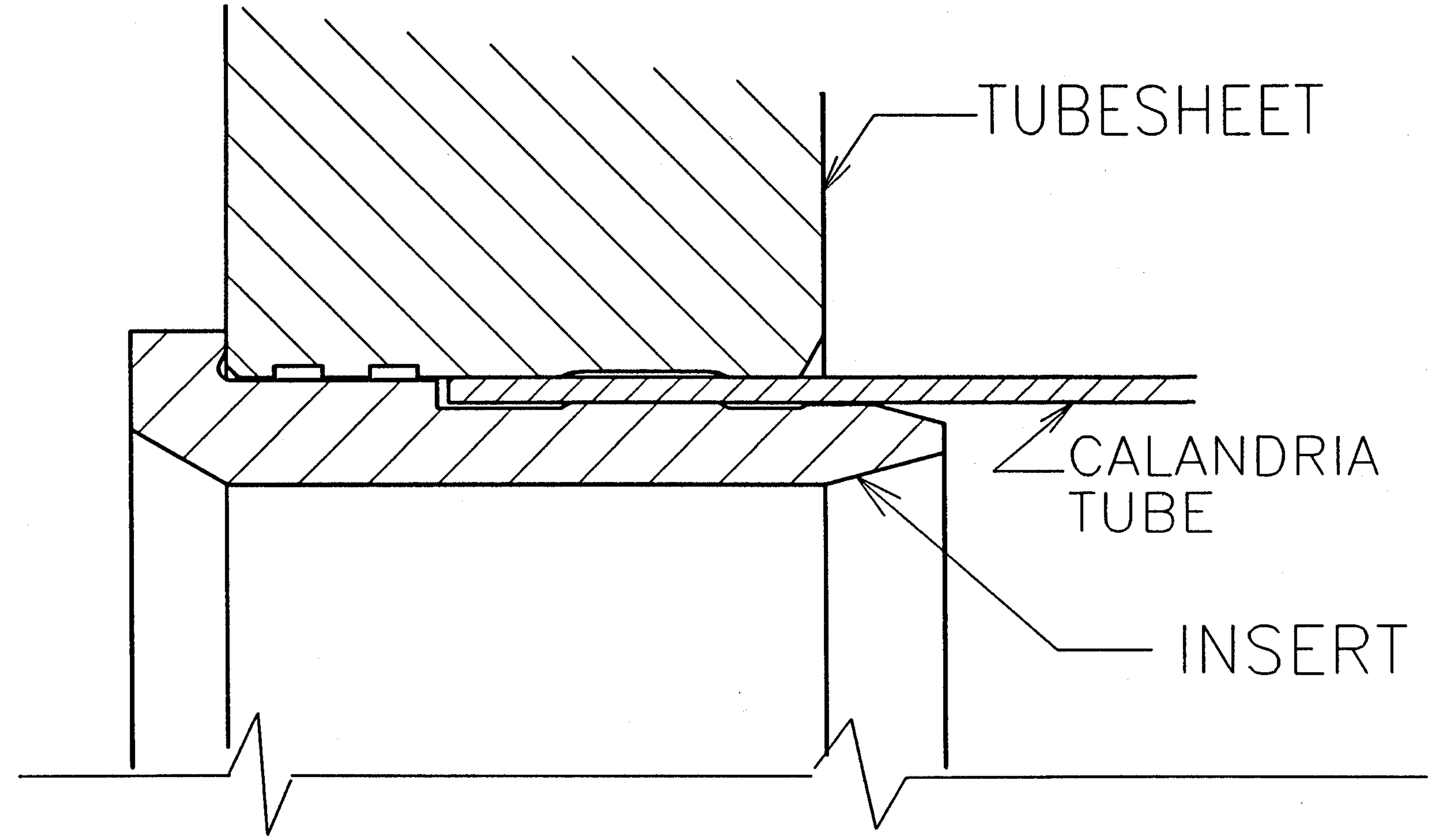

Figure 4: Calandria Tube-to-Tubesheet Joint - Assembly before Roll-Expansion

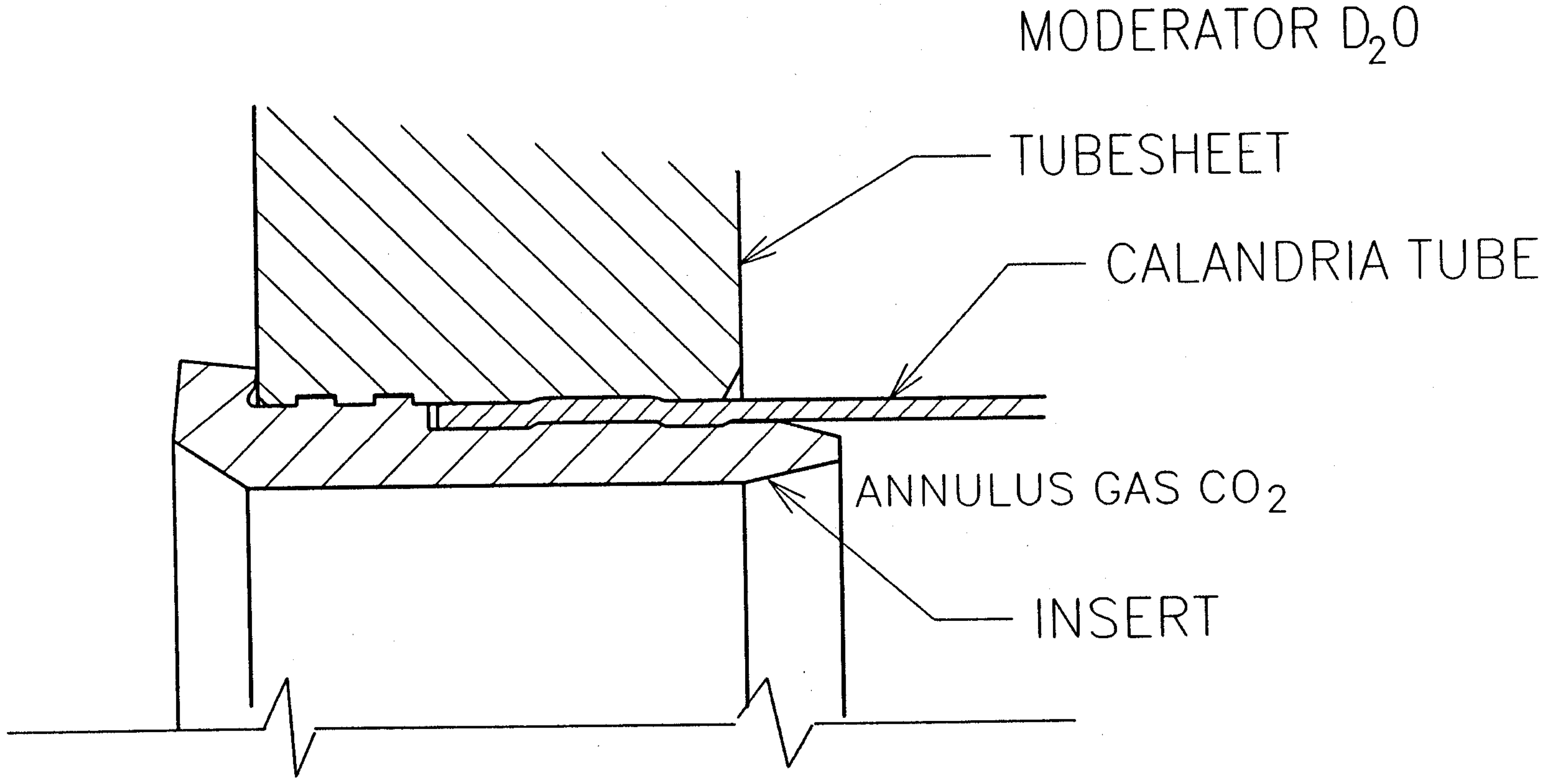

Figure 5: Calandria Tube-to-Tubesheet Joint - After Roll-Expansion

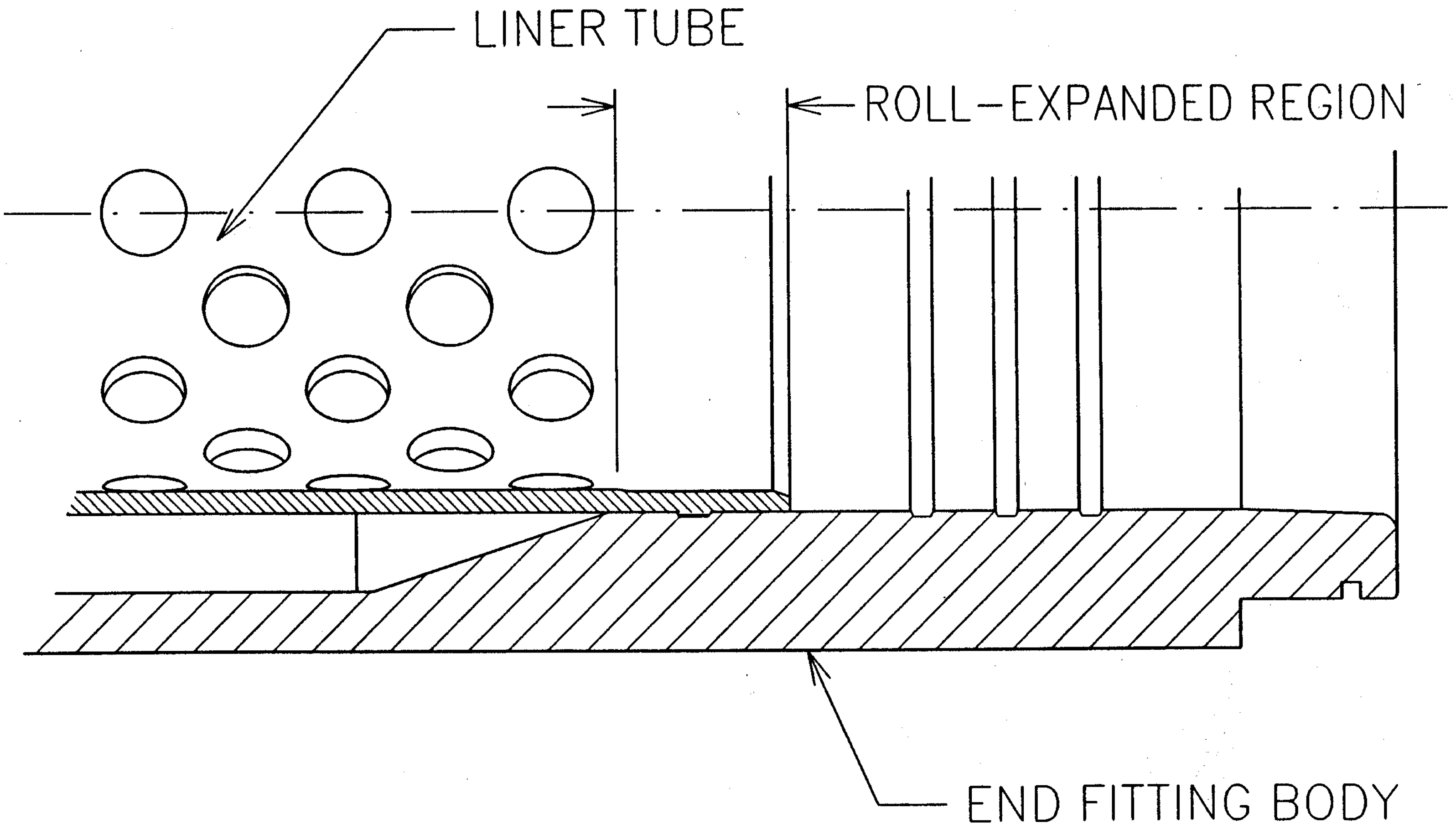

Figure 6: Liner Tube-To-End Fitting Roll-Expanded Joint

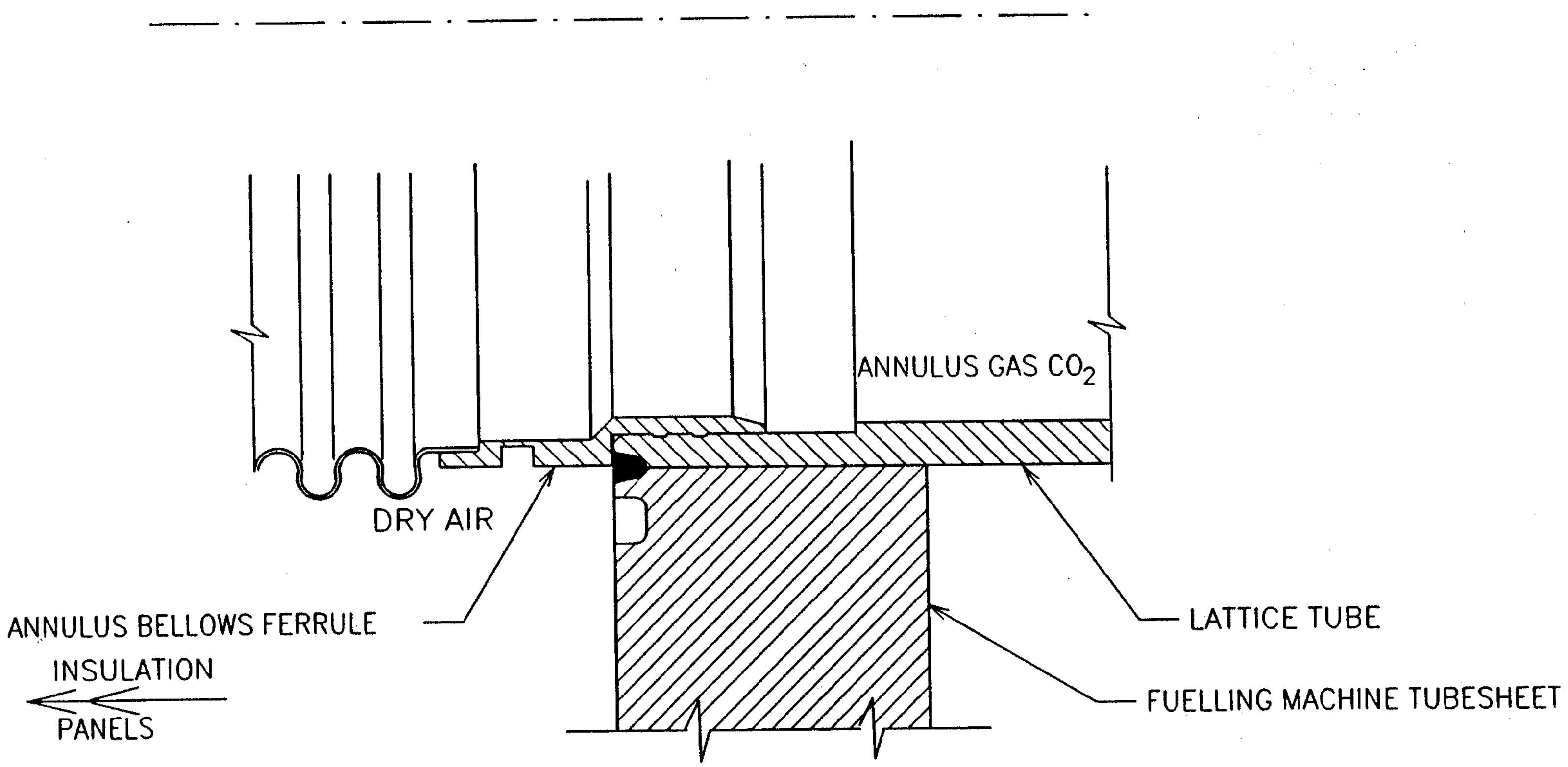

Figure 7: **Annulus Bellows to Lattice Tube Roll-Expanded Joint**

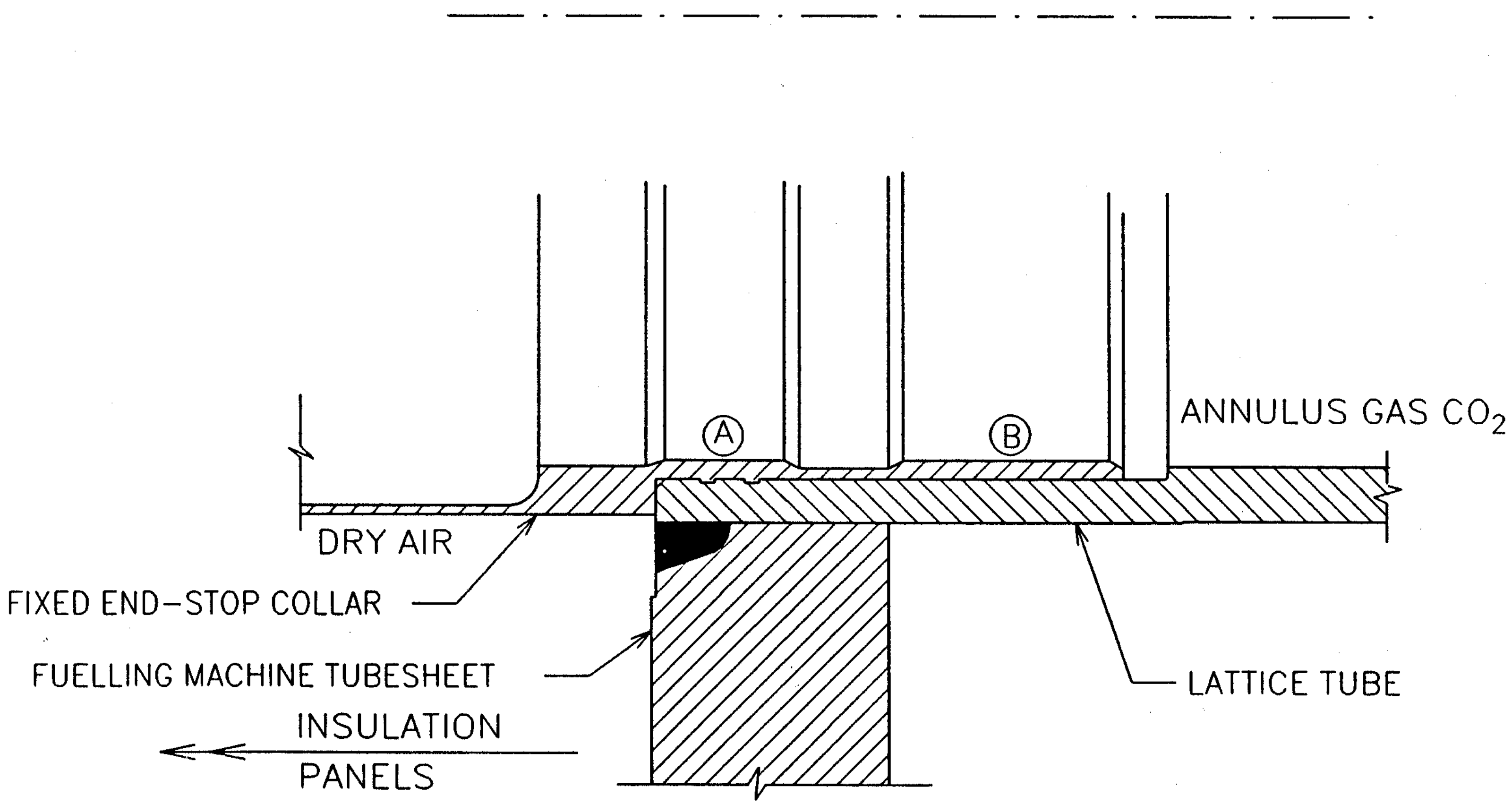

Figure 8: **End-Stop Collar to Lattice Tube Roll-Expanded Joint**

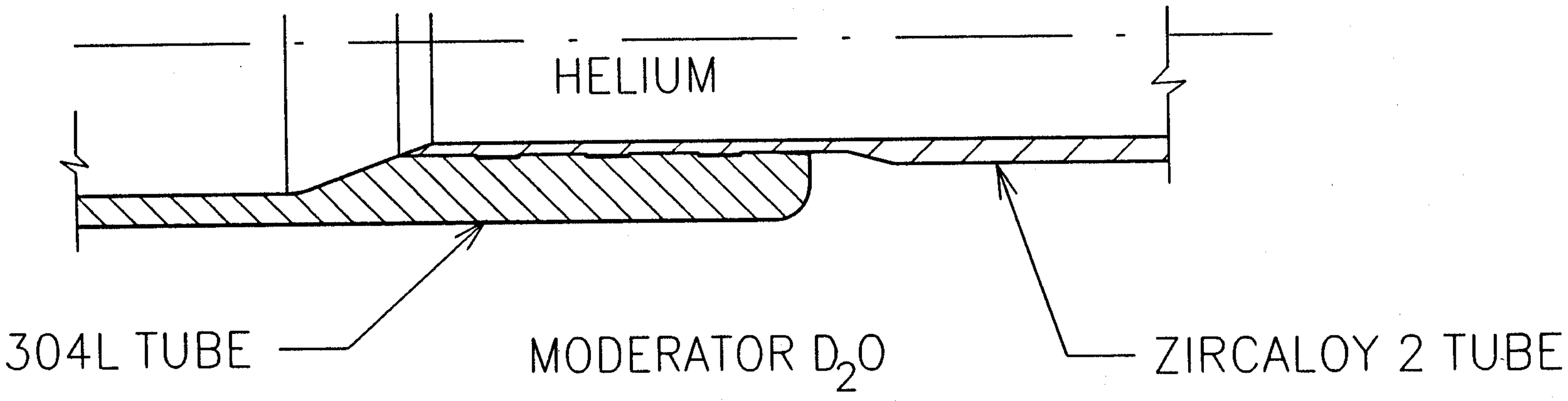

Figure 9: Flux Detector Guide Tube Roll-Expanded Joint